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# Recent Results on the Higgs Boson Properties in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel at CMS

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## ABSTRACT

The latest results on the measurement of the properties of the new boson with mass around 125 GeV are reported. The analysis uses pp collision data recorded by the CMS detector at the LHC, corresponding to integrated luminosities of  $5.1 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  and  $19.6 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . The boson is observed in the

$H \rightarrow ZZ \rightarrow 4\ell$  channel ( $\ell = e, \mu$ ) and its mass is measured, giving the most precise result ever achieved. Moreover, the first experimental constraint on Higgs total width using  $H \rightarrow ZZ \rightarrow 4\ell$  events is presented, setting an upper limit of 33 MeV at 95% confidence level (42 MeV expected). The spin-parity of the boson is studied and the pure scalar hypothesis is found to be consistent with the observation, when compared to the other spin-parity hypotheses. No other significant Standard Model Higgs-like excess is found in the search and upper limits at 95% confidence level exclude the range 129.5 -832.0 GeV.

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# 1 Introduction

The latest results on the measurement of the properties of the new boson with mass around 125 GeV [1] [2] are measured in the  $H \rightarrow ZZ \rightarrow 4\ell$  decay channel ( $\ell = e, \mu$ ). The analysis uses pp collision data recorded by the CMS detector [3] at the LHC, corresponding to integrated luminosities of  $5.1 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  and  $19.6 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ .

## 2 Analysis Strategy

The  $H \rightarrow ZZ \rightarrow 4\ell$  analysis [4] is based on the reconstruction, identification and isolation of leptons. Each signal event consists of two pairs of same-flavor and opposite-charge leptons in the final state, isolated and with high transverse momentum, and it is compatible with a  $ZZ$  system, where one or both  $Z$  bosons can be off-shell. The sources of background for the  $H \rightarrow ZZ \rightarrow 4\ell$  channel are the irreducible four-lepton contribution from direct  $ZZ$  (or  $Z\gamma^*$ ) production, very similar to the signal, the reducible background arising from  $Zb\bar{b}$  and  $t\bar{t} \rightarrow 4\ell$  decays and the instrumental contribution due to a misidentification of the leptons.

In order to separate signal from background events, a kinematic discriminant is defined ( $\mathcal{D}_{bkg}^{kin}$ ), depending on the five production and decay angles and the  $Z$  boson masses. These variables fully describe the event topology and have a high discriminating power. The  $\mathcal{D}_{bkg}^{kin}$  discriminant [5] is defined as

$$\mathcal{D}_{bkg}^{kin} = \frac{\mathcal{P}_{sig}^{kin}}{\mathcal{P}_{sig}^{kin} + \mathcal{P}_{bkg}^{kin}},$$

where  $\mathcal{P}_{sig}^{kin}(bkg)$  is the probability for an event with a given topology (angles and masses) to come from a signal (background) process.

## 3 Significance and Signal Strenght

The minimum of the local p-value is reached at  $m_{4\ell} = 125.7 \text{ GeV}$  (Fig. 1, left) and it corresponds to a local significance of 6.8 (for an expectation of 6.7). This is the only significant excess in the range  $m_H < 1 \text{ TeV}$ . The parameter that describes the magnitude of the Higgs signal is the signal strength modifier, defined as the ratio of the observed cross section and the cross section predicted by the SM ( $\mu = \sigma_{obs}/\sigma_{SM}$ ). The measured value of  $\mu$  obtained at the best fit mass ( $m_H = 125.6 \text{ GeV}$ ) is:

$$\mu = 0.93_{-0.23}^{+0.26}(stat.)_{-0.09}^{+0.13}(syst.).$$

## 4 Mass Measurement

The mass measurement is performed with a three-dimensional fit using for each event the four-lepton invariant mass ( $m_{4\ell}$ ), the associated per-event mass error ( $\mathcal{D}_m$ ) and the kinematic discriminant ( $\mathcal{D}_{bkg}^{kin}$ ). Per-event errors are calculated from the individual lepton momentum errors and including them in the fit allows to gain 8% improvement in the Higgs boson mass measurement uncertainty. The fit procedure gives  $m_H = 125.6 \pm 0.4(stat.) \pm 0.2(syst.) \text{ GeV}$  (see Fig. 1, right).

## 5 Spin-Parity Measurement

In order to determine the spin and the parity of the new boson, a methodology with kinematic discriminants is used. Two discriminants are defined, in order to separate SM Higgs from background events ( $\mathcal{D}_{bkg}$ ) and to discriminate an alternative hypothesis from the SM Higgs ( $\mathcal{D}_{JP}$ ). The different spin-parity hypotheses are thus tested using the two-dimensional likelihood  $\mathcal{L}_{2D} = \mathcal{L}_{2D}(\mathcal{D}_{JP}, \mathcal{D}_{bkg})$ .

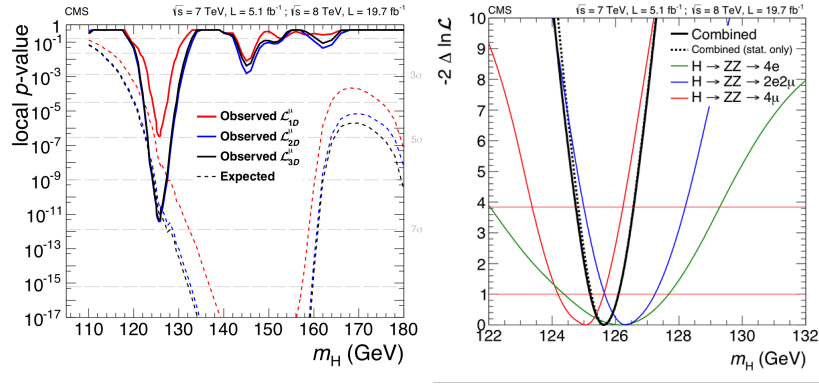


Figure 1: Significance of the local excess with respect to the SM background expectation as a function of the Higgs boson mass in the low mass range (left): red is 1D model ( $m_{4\ell}$ ), blue is 2D model ( $m_{4\ell}$ ,  $\mathcal{D}_{bkg}^{kin}$ ) and black is 3D model ( $m_{4\ell}$ ,  $\mathcal{D}_{bkg}^{kin}$ ,  $\mathcal{D}_{jet}$  or  $p_T^{4\ell}$ ). Likelihood scan as a function of mass obtained from the 3D test statistics for the different final states and their combination (right).

The distribution of the test statistic  $q = -2\ln(\mathcal{L}_{JP}/\mathcal{L}_{SM})$  is determined and it is examined with generated samples for  $m_H = 125.6$  GeV.

A confident levels (CLs) criterion is defined as the ratio of the probabilities to observe, under the  $J^P$  and  $0^+$  hypotheses, a value of the test statistic  $q$  equal or larger than the one in the data. The data disfavor the alternative hypotheses  $J^P$  with a CLs value in the range 0.001 -10% (see Fig. 2).

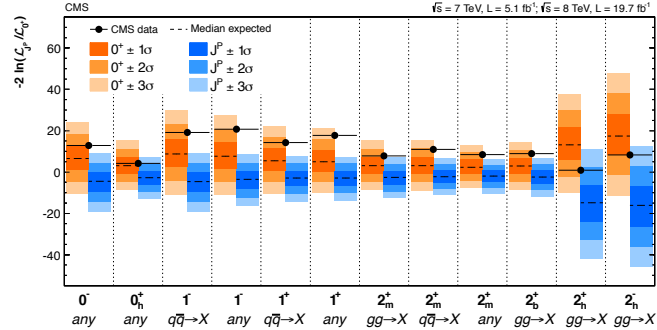


Figure 2: Summary of the expected and observed values for the test-statistic  $q$  distributions for the twelve alternative hypotheses tested with respect to the SM Higgs boson.

## 6 Width Measurement

At  $m_H = 125.6$  GeV, the Standard Model predicts a Higgs boson decay width ( $\Gamma_H$ ) of 4.15 MeV. A direct measurement at the resonance peak is thus strongly limited by experimental resolution, but it is possible to constrain the Higgs boson width using its off-shell production and decay away from the resonance [6]. Indeed, the integrated cross sections in the resonant and off-shell regions are

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{on-shell} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}, \quad \sigma_{gg \rightarrow H \rightarrow ZZ}^{off-shell} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2},$$

where  $g_{ggH}$  and  $g_{HZZ}$  are the couplings of the Higgs boson to gluons and Z bosons, respectively. Therefore, the value of  $\Gamma_H$  can be extracted by measuring the ratio of the production in the off-shell and on-shell region, taking into account the destructive interference with continuum  $gg \rightarrow ZZ$ , which is not negligible at high masses. In order to separate  $gg \rightarrow ZZ$  events from the  $q\bar{q} \rightarrow ZZ$  process, the dominant background of the analysis, a kinematic discriminant is built ( $\mathcal{D}_{gg}$ ).

A likelihood function is defined for both the off-shell and the on-shell region, depending on the total probability distribution functions

$$P_{tot}^{off-shell} = \mu_{ggH} \times (\Gamma_H/\Gamma_0) \times P_{sig}^{gg} + \sqrt{\mu_{ggH} \times (\Gamma_H/\Gamma_0)} \times P_{int}^{gg} + P_{bkg}^{gg} + P_{bkg}^{q\bar{q}} + \dots$$

$$P_{tot}^{on-shell} = \mu_{ggH} \times P_{sig}^{gg} + P_{bkg}^{gg} + P_{bkg}^{q\bar{q}} + \dots$$

and the parameters  $\Gamma_H$  and  $\mu_{ggH}$  are left unconstrained in the fit. The simultaneous maximum likelihood fit leads to an observed (expected) upper limit of  $\Gamma_H < 33$  MeV (42 MeV) at 95% C.L., i.e. 8.0 (10.1) times the Standard Model prediction (Fig. 3).

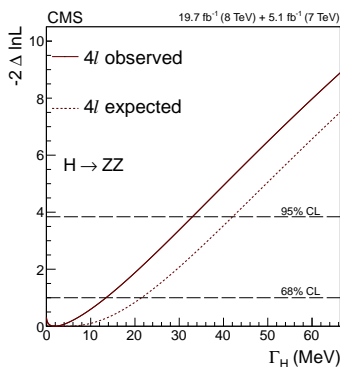


Figure 3: Likelihood scan of the  $\Gamma_H$  in the  $4\ell$  final state.

## References

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